

# Rocketdyne/Westinghouse Nuclear Thermal Rocket Engine Modeling

October 22, 1992  
Jim Glass

## Systems Approach Needed for NTR Design Optimization

Nuclear rocket engine systems, like chemical engines, require a systems-oriented approach to the selection and refinement of an optimum design. This approach stresses that all subsystems and components must be optimized or designed together; the goal is to achieve the best possible overall system design.

A well-anchored and validated steady-state design model is required, one which treats all important characteristics and phenomenology of the system elements, together with technology limits and constraints. The program must provide sufficient design detail to fully characterize the engine system, and to provide confidence in the design. The detailed system design file is also passed to the Steady-State Off-Design and Transient models, where it forms the basis of the hardware description needed to initialize the off-design or transient simulation.

Rocketdyne's Steady-State Design Optimization model is based on known and proven methodologies such as those shown. It performs a "rubber engine" conceptual design, and uses scaling only when appropriate. Physical or first-principles component models are preferred. The code performs constrained optimization, with both implicit and explicit constraints. These constraints reflect technology level, risk, reliability, and other limits on the design, and help to ensure that a practical and achievable design is obtained.

## Systems Approach Needed for NTR Design Optimization

---

- All elements of engine system optimized together
  - Reactor
  - Turbomachinery
  - Feed System
  - Controls
  - Nozzle and throat
  - Cooling and heat exchange
- Design model based on anchored and proven methodologies
  - JANNAF Performance Prediction
  - NBS (NIST) Thermodynamic Properties
  - CPIA 246 Expansion Process Losses
- "Rubber Engine" conceptual design versus scaling approach
  - First principles analysis where appropriate
  - Provides design detail
  - Reflects technology level and design constraints
    - Technology year
    - Risk/reliability/cost



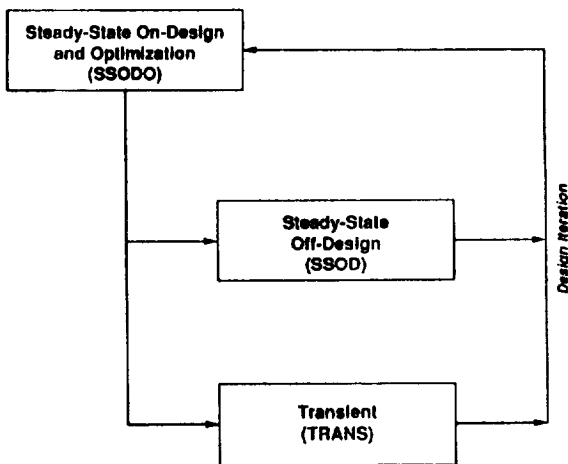
Rockwell International  
Rocketdyne Division

### Generic NTR Engine Power Balance Codes

Rocketdyne's approach to NTR engine system modeling utilizes three separate codes, which are linked by a common hardware description file. The Steady-State Design Optimization program develops an optimized system design, based on user inputs, a schematic description file, and optimization constraints. The output of the design program is a hardware definition file which can be passed to the Steady-State Off-Design code or to the Transient code.

Both of the latter codes (SSDO and TRANS) are off-design models in the sense that they seek to analyze the behavior and response of fixed hardware to changes in control settings, component characteristics, or start/shutdown. The Design Optimization model is an "on-design" model, or "rubber engine" model, which seeks to find the best design operating point to meet user requirements and technology constraints.

## Generic NTR Engine Power Balance Codes



מחלקת המחקר והפיתוח

## Rocketdyne Nuclear Thermal System Code Heritage/Pedigree

The Rocketdyne NTR system models have been under continuous development at Rocketdyne since 1975, under both company and government funding. These codes form the basis of the company's engine preliminary design capability.

These codes or variants have been successfully utilized to design a variety of flight-type engine systems, including the RS-44, XLR-132, STME, STBE, RSX, and IME engines.

In addition, the codes have been validated by generating "designs" for current and past hardware, including F-1, J-2, SSME, and Russian engine designs.

# Rocketdyne Nuclear Thermal System Code

## Heritage/Pedigree

- Elements of engine system model under continuous development since 1975.
- Used as preliminary design and optimization tool at Rocketdyne.
- Used to design:

ASE	20,000 lb thrust O2/H2 space engine
RS-44	15,000 lb thrust O2/H2 space engine
XLR-132	3,750 lb thrust NTO/MMH space engine
STME	650,000 lb thrust O2/H2 space transportation engine
STBE	750,000 lb thrust O2/hydrocarbon booster engine
RSX	237,000 lb thrust O2/RP-1 booster engine
IME	30,000 lb thrust O2/H2 space engine

- Validated against current and past hardware:

F-1
J-2
SSME

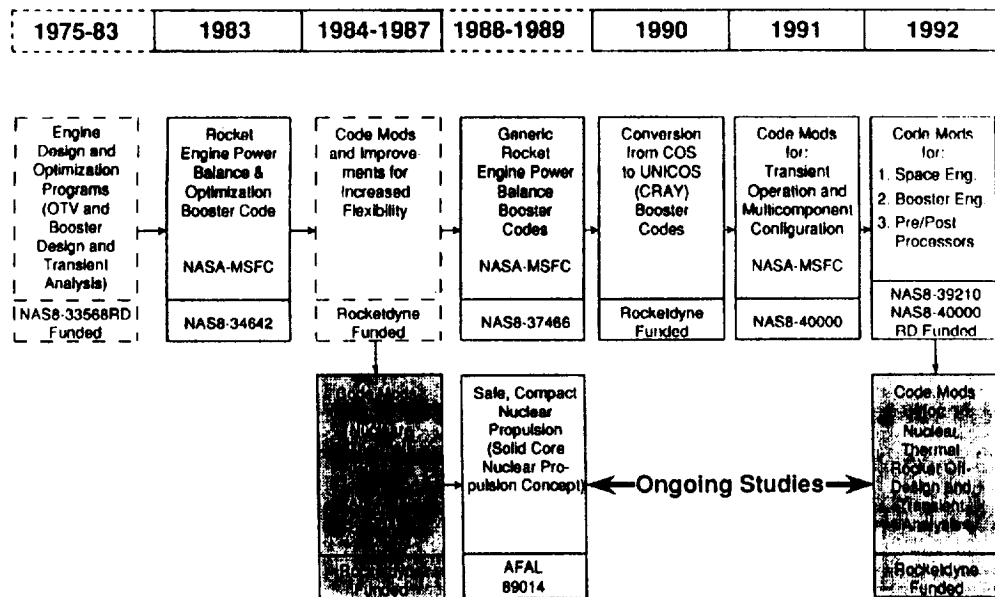
Russian RD-170 booster engine
Russian RD-0120 engine
Russian RD-701 tripropellant engine



## Code History

This chart illustrates the continuous, ongoing effort on the Nuclear Thermal System Model and its precursors. Rocketdyne internal funding has supplemented a series of NASA contracts in development of a robust, validated and flexible engine system modeling code. Recent work (since 1987) has focused on modifications to the code to enable modeling of Nuclear Thermal Rocket systems. A recent Air Force study, the Safe Compact Nuclear Propulsion study, utilized results of the code. Ongoing Rocketdyne in-house studies have also made extensive use of the code results.

## Code History



and no. 00-20-01-151

### NTR System Model--Code Features

Key features of Rockwell's NTR system model include variable schematic analysis, high-fidelity propellant properties, prismatic core geometry, accurate turbomachinery, heat-transfer, and performance estimation algorithms, and a nonlinear, constrained optimization routine.

The variable schematic capability uses a data-driven approach, in which all design modules and algorithms are contained within a single program, and appropriate modules are called under control of an executive which traverses the input schematic network. This is different from a variable-code approach, in which a new model is generated and re-compiled for each new system configuration. The data-driven approach maximizes code flexibility, does not entail difficulties in traceability of code results, and enables higher-speed modeling (no compile step).

Well-anchored turbomachinery and heat-transfer calculations are included, which improve model accuracy and enhance confidence in the resulting system design.

Use of NBS/NIST and JANNAF propellant and performance methods also increases code fidelity.

The non linear, constrained optimization routine enables comparison of competing candidate system configurations on a common basis; i.e., "best possible" design points for all candidates can be compared.

## NTR System Model Code Features

---

- Variable Schematic
  - Code flexibility
  - Ease of modeling new concepts
  - Fixed code/variable data
- NBS/NIST Propellant Properties
  - Accurate energy balance
  - Accurate flow schedule
  - Hydrogen, methane, CO<sub>2</sub>, or ammonia propellants
- Prismatic reactor core geometry
  - Particle-bed and wire-core may be added
- NTR-Unique components
  - Cooled structure
  - Reflector/moderator
  - Nozzle heat load accounting
- Rocketdyne Turbomachinery Design Routines
  - Historically-anchored T/M performance and envelope
  - Centrifugal or axial pumps
- Rocketdyne Heat Transfer Correlations
  - Accurate prediction of jacket heat loads and  $\Delta P$
- JANNAF/CPIA Performance Estimation
  - Accurate and rapid delivered performance prediction
  - Accounts for all loss mechanisms (B/L, Kinetics, Divergence)
- Nonlinear, Constrained Optimization Capability
  - Minimize or maximize any system variable



### Software Capabilities

The present code is capable of optimizing the system design for Nuclear Thermal Rocket engines in the 10,000 to 250,000 pound thrust range. Key features of the code include the input-controlled variable schematic analysis capability, detailed NBS (NIST) hydrogen properties, a graphic preprocessor (which eases user interaction with the model), and multiple component capability. The multiple component feature enables modeling of engine systems with multiple redundant turbopumps, and design of systems capable of pump-out operation.

Transfer of engine system design information from the design module to the off-design or transient code is possible.

Future (planned) enhancements to the existing models includes incorporation of additional propellants such as ammonia, carbon dioxide, and methane. These propellants have been mentioned as possible alternate propellants, especially for in-situ propellant-based missions. A graphic post-processor is being prepared, which will present the code output in graphical form for ease of interpretation.

Work on the Steady-State Off-Design and Transient codes to incorporate higher-fidelity nuclear elements is planned. The off-design models will also be extended to enable specification of as-measured hardware characteristics (such as pump H-Q maps, turbine maps, etc.).

# Software Capabilities

## • Current

**Optimize and size engines of 10K to 250K thrust**

**Input-controlled variable-schematic capability**

**Hydrogen propellant**

**Graphic preprocessor**

**Multiple component capability: 40 components**

**Automatic configuration transfer**

**Steady-state design optimization**

## • Future

**Other propellants: Ammonia, CO<sub>2</sub>, CH<sub>4</sub>**

**Graphic postprocessor**

**Steady-state off-design and transient models**

**Off-design models will accept actual hardware characteristics**



## Steady State Model

The Steady-State Design Optimization model accepts user inputs consisting of general user inputs (thrust, chamber pressure, area ratio, etc.), a schematic definition file, optimization specifications and constraints, and reads data from a knowledge base which provides propellant properties, theoretical performance tables, and other information on components and subsystems.

The major elements of the Steady-State model include a schematic analyzer, component models, optimizer, thermodynamic state computations, and performance calculations.

The Schematic Analyzer uses the user-input schematic definition file to develop the interconnections between the engine system elements. The schematic is described in terms of a grid or array of nodes and the connections between the nodes. The schematic analysis routine controls the flow of the program by repeatedly traversing the component/node network until convergence has been obtained.

Component models provide algorithms describing the operation, design and sizing of the engine system components, such as turbopumps, heat-exchange elements, reactor, structural jacket, and nozzle.

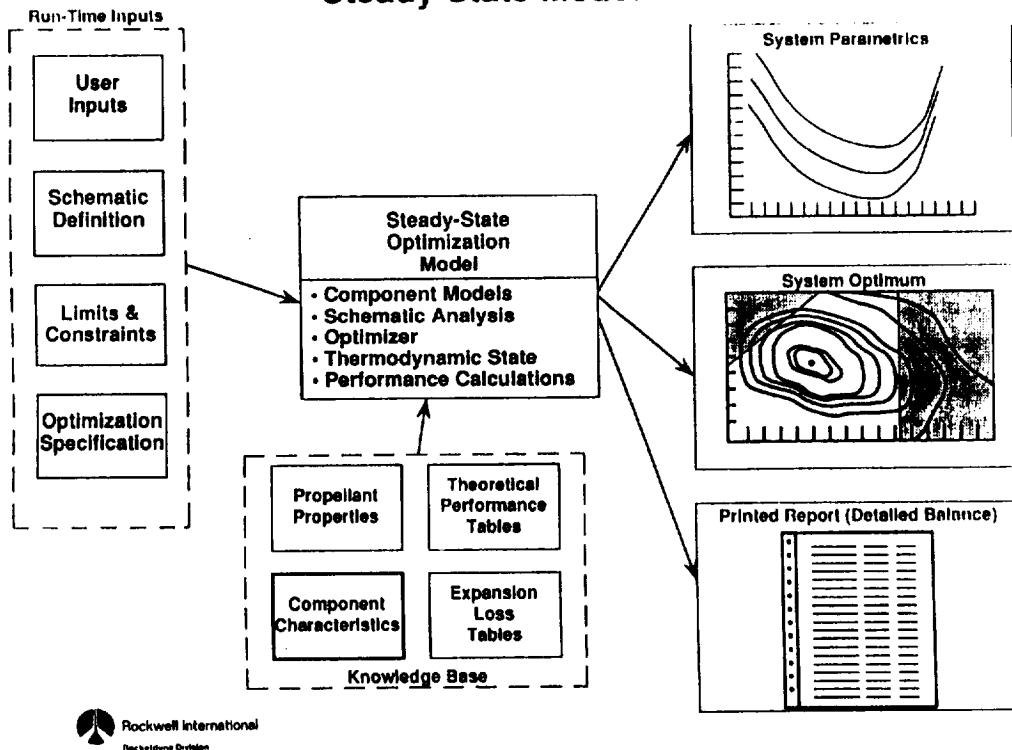
The Optimizer varies selected independent variables (such as pump speed, turbine pressure ratio, or chamber pressure) in order to minimize or maximize a selected object function subject to a set of constraints.

Thermodynamic state computations are performed under control of the schematic analyzer to track the detailed thermodynamic state of the propellant at each engine system station.

Performance calculations are performed in order to develop theoretical and delivered engine and thrust-chamber performance and associated loss terms based on nozzle geometry, operating temperature, and inlet propellant state.

In addition to providing an optimum design point, the model can be operated in a parametric mode to enable generation of parametric curves which describe families of similar system designs. Printed reports and a hardware definition file are also produced.

## Steady State Model

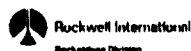
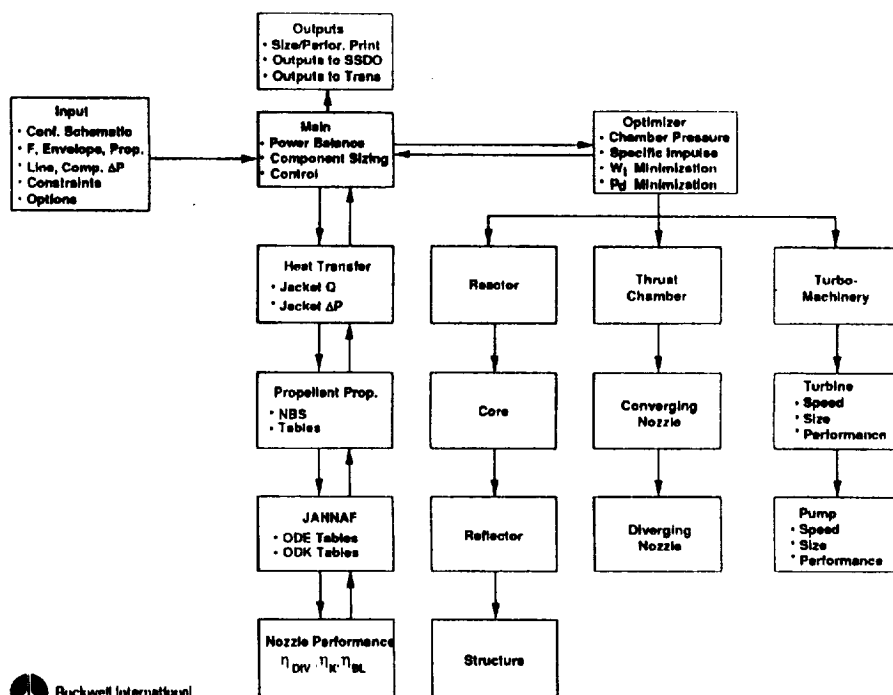


### NTR Engine Optimizer Code -- Logic

This chart illustrates the block-level logic of the Steady-State NTR design code. The figure shows that the main control routine is responsible for driving the schematic analysis and performing component sizing and performance calculations. The optimizer routine is used to maximize or minimize a selected object function by selecting a set of independent variables which control one or more aspects of component or subsystem design.



## NTR Engine Optimizer Code - Logic



author 00-27-01-01

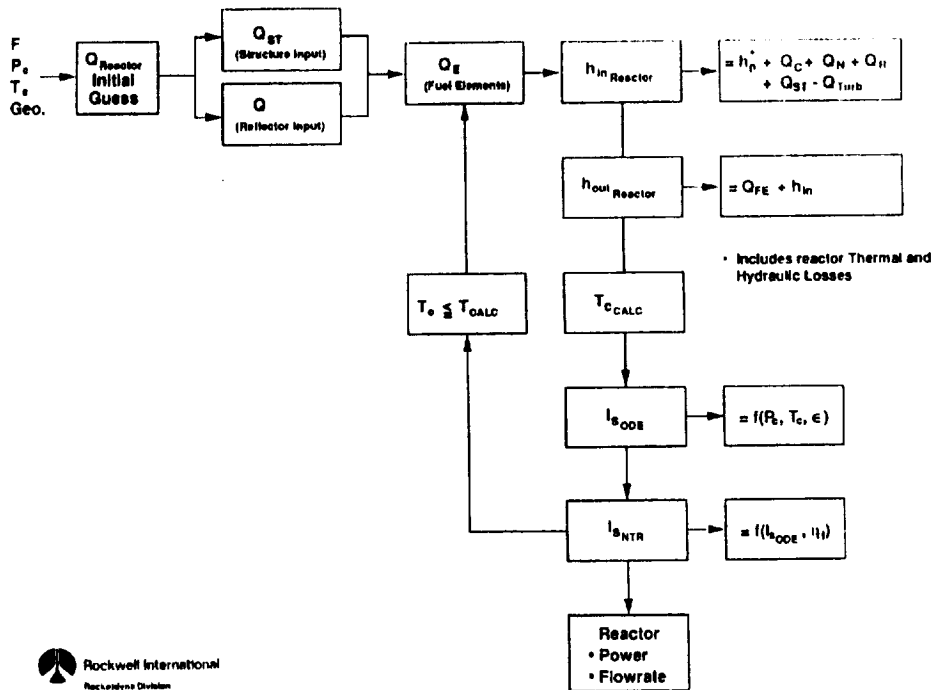
### Reactor Power Calculation Logic

The Steady-State code presently contains a lumped reactor model, which essentially treats the reactor as a heat source, but does not perform detailed reactor element sizing. An initial estimate of reactor power (heat) is derived from inputs of thrust, chamber pressure, and desired gas exit temperature. Separate estimates of structure and reflector heat loads are developed based on correlations of detailed heat-transfer analysis.

An initial estimate of the heat load from the reactor is made, from which the reactor exit enthalpy can be computed. The reactor outlet temperature is then computed from the total reactor heat and inlet conditions, and this temperature is compared with the desired exit temperature. If necessary, the reactor heat is readjusted until the exit temperature converges. Once the exit temperature is known, the theoretical specific impulse and C-star can be calculated.

The reactor flowrate is then known, as is net reactor power level.

## Reactor Power Calculation Logic



amhr 09 2294 14

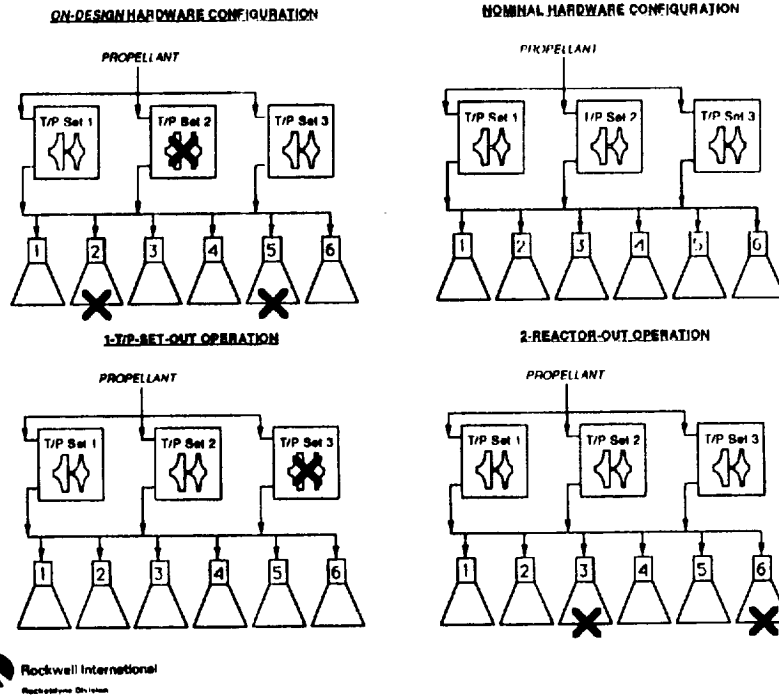
## Sample Multi-Component Configuration

Redundant design configuration of NTR propulsion systems is important due to the potential impact of an engine failure on the mission and on the survival of the crew. Design of redundant turbopump sets and/or multiple reactor/thrust chamber sets is attractive because it enables robust propulsion systems which can tolerate a single failure or even multiple failures and continue to operate. Mission success and crew survival can be greatly enhanced by careful application of redundant design philosophy.

The NTR design code is capable of modeling various system configurations which incorporate multiple turbopump and reactor/thrust chamber sets. One possible type is the incorporation of fully-redundant powerhead and reactor/thrust chamber assemblies, which are intended to remain non-operating unless/until one of the operating sets fails. The failed set is then shut down and the "spare" set takes its place. Another possibility is to design multiple powerhead/thrust chambers which are designed to operate in parallel, with no spares. Failure of a turbopump or reactor/thrust chamber would result in shutdown of the entire subsystem with continued operation of the remaining powerheads and reactor/thrust chambers. A third option involves design of multiple turbopump sets, a subset of which (say two out of three) are capable of operating all of the multiple thrust chambers at their design point. A failure of a pump set would still allow on-design operation with the remaining turbomachinery. However, prior to failure, all turbopump sets would operate off-design (throttled or de-rated). Finally, the system can be designed to enable failure of multiple thrust chambers, with the multiple turbopump sets continuing to operate to supply the remaining thrust chamber sets.

Loss of reactors has additional implications: A reactor will continue to produce power from decay heat and from neutron leakage (from adjoining reactors in the engine cluster). Careful consideration of this continued heating must be made from a mission-safety viewpoint. It may be necessary to jettison a failed reactor if the continued heating cannot be adequately controlled and/or suppressed.

## Sample Multi-Component Configuration

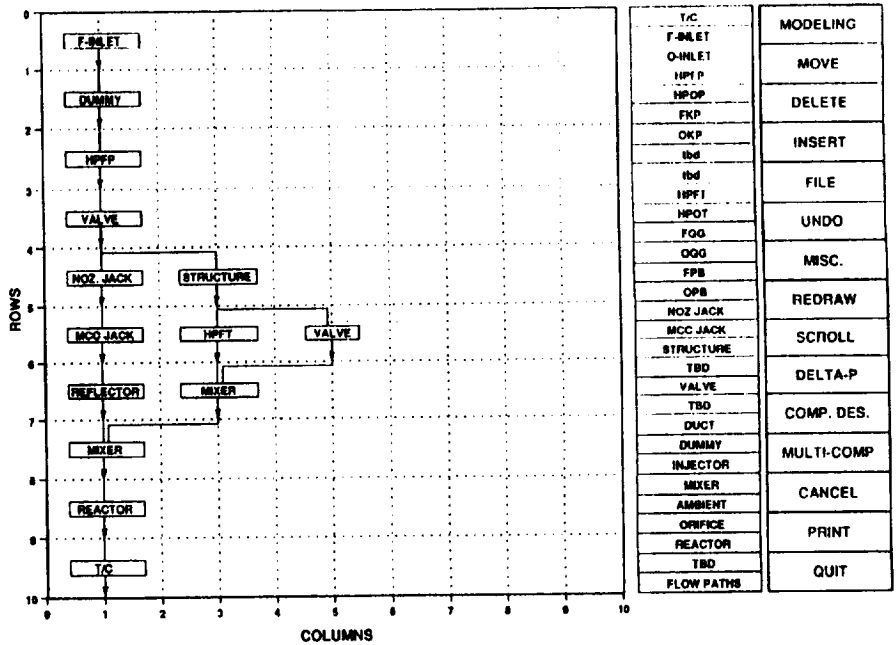


### Configuration Preprocessor

This chart illustrates the graphical pre-processor. The preprocessor presents a grid on the left side of the screen, which is employed by the user to draw the engine components and define their interactions. A main menu (right side of screen) selects modes and operations, and a sub-menu (to left of main menu) presents component choices.

In use, the user selects a component from the sub-menu and then indicates the inlet and exit node locations for the selected component on the schematic grid. By successively adding components, the preprocessor builds an internal representation of the schematic connections, pressure drops, and component characteristics of the desired engine system configuration. When complete, the schematic description and other information is written to an output file, which can then be read by the Steady-State, Off-Design, or Transient codes.

# Configuration Preprocessor



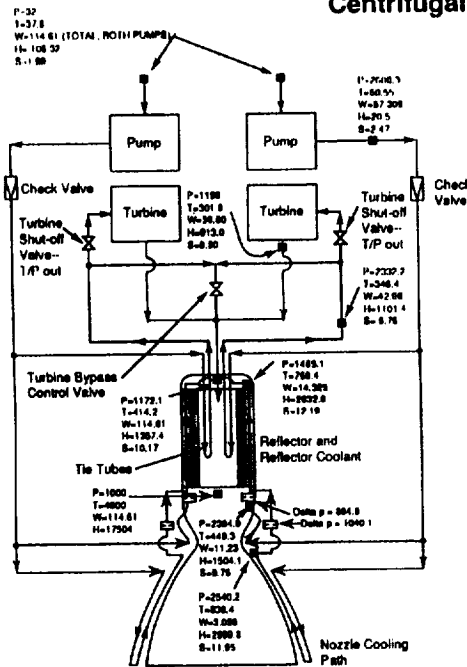
## NTR Design Code Output

A typical printout of the Steady-State NTR design code is presented in this chart. As can be seen, the level of design detail available is high. Summary printouts of reactor and nozzle design characteristics, tie-tubes (cooled structure), performance, and turbomachinery design variables are included. A detailed listing of all propellant state properties at each system station is printed, and a system mass estimate is also provided.

[illegible]

This chart illustrates a system design balance performed with the NTR Steady-State Design code. When the graphic post-processor is available, an annotated schematic diagram similar to that shown will be automatically generated by the post-processor.

## 100K NTR, Expander Cycle, Dual T/P\* Centrifugal Pump



 Rockwell International  
Rockwell International

### DESIGN VALUES:

PUMP FLOWRATE (TOTAL)	114.61 LB/SEC
PUMP DISCHARGE PRESSURE	2,606 PSIA
NUMBER OF PUMP STAGES	?
PUMP EFFICIENCY	70.71 %
TURBOPUMP RPM	50,540 RPM
TURBOPUMP POWER (EACH)	10,282 HP
TURBINE INLET TEMP	346.4 °F
NUMBER OF TURBINE STAGES	2
TURBINE EFFICIENCY	81.71 %
TURBINE PRESSURE RATIO	1.95
TURBINE FLOW RATE (EACH)	38.60 LB/SEC
REACTOR/ENGINE THERMAL POWER	2,075 MW
FUEL ELEMENT TRANSFERRED POWER	1,952 MW
CORE THERMAL POWER (FUEL ELEMENT+TIE TUBE)	2,050 MW
ENGINE THRUST	100,000 LBF
NOZZLE CHAMBER TEMPERATURE	4,600 °R
CHAMBER PRESSURE (NOZZLE STAGNATION)	1,000 PSIA
NOZZLE EXPANSION AREA RATIO	200:1
NOZZLE PERCENT LENGTH	110%
VACUUM SPECIFIC IMPULSE (DLEFM III D)	872.5 SEC

Heat loads are as follows:

Nozzle-con (total):	35.15 MW
Nozzle-div (total):	18.80 MW
Reflector (total):	25.00 MW
Tie-Tubes (total):	98.00 MW

P = PSIA  
T = DEG R  
W = LB/S  
H = BTU/LB  
S = BTU/LB-R

\*Note: Flows Indicated are for one-half of system.

## Future Activities and Capabilities

Future capabilities to the NTR design software are listed in this chart. These enhancements are being added in a series of NASA- and company-funded efforts. The space engine thrust chamber and main pump subroutines are being upgraded to extend the thrust range over which they are applicable. Low pressure boost pump design capability for zero-NPSH operation designs is being added. These two efforts are being funded by MSFC for SEI application. However, the code improvements will also be directly applicable to NTR modeling.

Company-funded efforts will complete the optimization of reactor power, envelope, and weight; the full implementation of the pre- and post-processors, and the full implementation of the transient analysis reactor model.

## Future Activities and Capabilities

---

<u>Activity</u>	<u>Funding</u>	<u>Planned Completion</u>
Low pressure (boost) pump simulation	NAS8-40000	November 1992
Reactor power, envelope, weight optimization model	Rocketdyne	December 1992
Upgrade space engine design optimization	NAS8-39210	January 1993
Enhanced pre/post processors	Rocketdyne	March 1993
Transient analysis model (feed system, thruster, and reactor)	Rocketdyne	April 1993



### Generic NTR Code at Rocketdyne

The Rocketdyne Generic NTR code provides design versatility for all aspects of NTR system analysis (design, off-design, and transient), ease of use and user-friendly features through variable schematic features and pre- and post-processors, and system versatility because it can be operated on a variety of platforms, including VAX, Cray, Alliant, and Sun workstations.

As PC hardware continues to improve, it will soon be possible to port these codes to the PC platform and to operate them with acceptable speed and accuracy.

## Generic NTR Code at Rocketdyne

**Design Versatility:**      **Design Point Optimization**

**Off-Design**

**Transients**

**User Versatility:**      **Variable Schematic**

**Pre/Post-Processors**

**Auto Configuration Transfer**

**System Versatility:**      **VAX, CRAY, ALLIANT, Sun Workstations**

**Future: Improved PC platforms**



NP-TIM-92-001

### Rocketdyne NTR Model--Summary

This chart summarizes the essential message of this briefing: Rocketdyne has developed an NTR engine system modeling capability which emphasizes Utility and Fidelity.

Utility is based on the codes' flexibility and versatility, user-friendly features, ease of modification, and documentation.

Fidelity is based on use of first-principles methods, extensive validation against past flight designs and existing hardware, and accurate component and performance algorithms. The codes are adequate for use in preliminary design, screening, and trade studies. With further refinement and deepening, the codes will evolve into full "point-design" models.



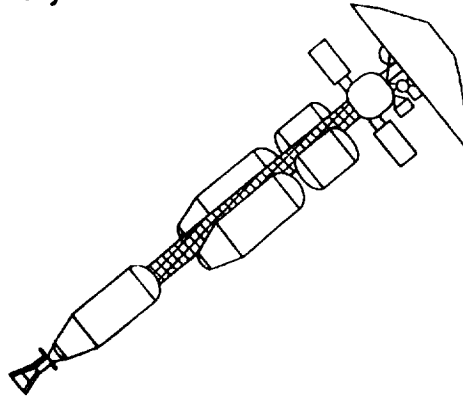
# Rocketdyne NTR Model

## Summary



### Utility

- Versatile
- User Friendly
- Easy Modification
- Fully Documented



### Fidelity

- First-Principles Analysis Methods
- Flight Engine Validated
- Accurate Component & Performance Algorithms
- Preliminary Design-Level Support



### Nuclear Thermal Rocket Modeling Directions

This chart illustrates Rocketdyne's vision of one possible direction in which NTR modeling activities might proceed. We believe that a collaboration among NASA/DOE, end-users, and industry will bring major benefits to the codes and models which are ultimately developed. Industry brings capabilities which compliment and enhance those already in place at NASA centers and national laboratories. Users concerns must be addressed to ensure that the codes developed are usable and meet actual needs. NASA/DOE leadership and direction are critical to successful code development.

## Nuclear Thermal Rocket Modeling Directions

---

